

Evidence for Shape Co-existence at medium spin in ^{76}Rb

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Abstract

Four previously known rotational bands in ^{76}Rb have been extended to moderate spins using the Gammasphere and Microball γ ray and charged particle detector arrays and the $^{40}\text{Ca}(^{40}\text{Ca},3\text{pn})$ reaction at a beam energy of 165 MeV. The properties of two of the negative-parity bands can only readily be interpreted in terms of the highly successful Cranked Nilsson-Strutinsky model calculations if they have the same configuration in terms of the number of $g_{9/2}$ particles, but they result from different nuclear shapes (one near-oblate and the other near-prolate). These data appear to constitute a unique example of shape co-existing structures at medium spins.

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One of the remarkable properties of the nuclear quantal many body system is its ability to minimize its energy by adopting different nuclear shapes for a relatively small cost in energy compared to the total binding energy. This, coupled with the shape driving effects of the odd nucleons can, in certain circumstances, result in different nuclear shapes being possible at low excitation energies in nuclei. Recent calculations [1] have pinned down the regions of the nuclear chart where nuclei may assume different shapes at close to groundstate energies. In some cases as many as four different minima, corresponding to different shapes, are found in the potential energy surface for a single nucleus. The degree to which the groundstate wavefunction becomes a mixture of these differently shaped states or if the minima give rise to individual nuclear states is still an open and interesting question.

Various reviews have been performed over the last 20 years on shape co-existence in atomic nuclei, with the most recent being by Heyde and Wood [2]. Potentially, one of the best examples of nuclear shape coexistence at low spins is found in the light lead nucleus, ^{186}Pb , where the first three excited 0^+ states are believed to result from spherical, oblate and prolate minima, respectively, in the potential energy surface [3]. This particular phenomenon of shape coexistence has been discussed in terms of intruder states based on proton particle-hole excitations across the $Z=82$ shell gap [2, 4, 5]. The phenomenon is also known to occur at much higher spins where many excited rotational bands can often be found. Since each band is usually built on different excited configurations this often results in different shapes that can change with spin. It is however only when the states are sufficiently similar and possess the same quantum numbers that one may see an interaction between rotational bands. Such interactions can then provide information about the degree of shape mixing.

The neutron deficient nuclei with mass $A = 70 - 80$ are located in a region of large deformed shell gaps [6]. Strong gaps exist at both oblate (34, 36) and prolate (36,38) nucleon numbers [7]. The first evidence for shape co-existence at low spins in this region was proposed in ^{72}Se [8] and a detailed review of all the early data was made by Wood et al. [4] some years later. More recently detailed studies of shape co-existence and mixing between the low-spin oblate and prolate states has been investigated in $^{72-78}\text{Kr}$ [7]. ^{76}Rb , which has 37 protons and 39 neutrons is located in the region of interest. However, whilst ^{76}Rb does not directly possess any of the nucleon numbers where large shell gaps occur for oblate shapes, there are long standing suggestions for the presence of shape coexistence in the nucleus at low spins [9] as well as indications for evidence of the phenomenon in $N=39$ isotopes of Ge, Se, Kr and Sr (see fig 38 of ref [2]). At moderate spins the nucleus has been found to be dominated by five very regular rotational structures [10]. In the present work these structures have been extended to spins of the order of $30\hbar$, with over 40 new γ rays being observed. The structures observed, and the interactions between them can be interpreted, with the aid of cranked Nilsson-Strutinsky (CNS) calculations, as providing evidence of an excellent example of the coexistence at moderate spins of oblate and prolate structures. Of particular interest is the fact that two bands can be interpreted as being constructed from the same basic configurations, i.e. with the same number of particles excited to the $g_{9/2}$ shell, but with very different shapes. To our knowledge, this is the first example of this kind of shape coexistence at high spin where the rotational bands in both minima are observed in an extended spin range. A further interesting feature is that it has been possible to extract approximate interaction matrix elements between the bands in the two minima at spin values $I \approx 12$ and $I \approx 20$, respectively.

The experiment was performed at the Argonne National Laboratory using the ATLAS accel-

erator to produce a ^{40}Ca beam at 165 MeV. This beam was used to bombard a $350\text{ }\mu\text{g}/\text{cm}^2$ ^{40}Ca target that was flashed on both sides with $150\text{ }\mu\text{g}/\text{cm}^2$ of gold to prevent oxidation. The reaction channel of interest in the present work was $^{40}\text{Ca}(^{40}\text{Ca},3\text{pn})^{76}\text{Rb}$. γ rays from ^{76}Rb were detected using the Gammasphere array [11], which consisted of 99 Compton suppressed Ge detectors, and identification of evaporated charged particles was performed using the Microball array [12]. An event was triggered on the condition of at least four of the HPGe detectors firing in prompt coincidence. A total of 1.5×10^9 high-fold events were recorded. The information from the Microball array, that provides the energies and directions of the detected charged particles, allowed for an offline event-by-event reconstruction of the momenta of the residual nuclei [13, 14], thereby resulting in an improved energy resolution for the γ -ray peaks.

Events coinciding with the detection of no α particles and 1 or 2 protons were used to help select the nucleus ^{76}Rb . Attempts to enhance the channel of interest (3pn) using the 3p-gated data and the total energy plane (TEP) method [15] did not improve the signal to background significantly. This is due to the finite charged particle detection efficiencies and the strongly overlapping locations in the 3p-gated TEP of the 3pn events in which the neutron is not detected, 4p events in which one of the protons was not detected, and α 3p events in which the α -particle was not detected. An open TEP gate was thus utilised in order to maximise statistics. The events, with the above particle gating conditions, were used to create a γ - γ - γ cube which was used to extend the known [10] energy level decay scheme for the nucleus. The level scheme, deduced with the aid of the RADWARE [16] graphical analysis package, is shown in Fig. 1. The spins and parities of the extended rotational structures are assigned on the assumption that the observed transitions are stretched E2's, since it was not possible to obtain sufficiently accurate directional correlation from oriented state (DCO) values to unambiguously confirm these.

Fig. 2 shows some partial spectra in support of the proposed level scheme and to illustrate the overall level of statistics and quality of the data. The double gating conditions used to create the spectra shown from the E_γ - E_γ - E_γ cube are described in the relevant figure captions. The present work agrees with the previous work [10] for the low spin part of the decay scheme but most bands have been extended to considerably higher spin values. The $\alpha = 0, 1$ signatures of 'band 1' with positive parity have been extended by 6 and 5 transitions, respectively. The negative parity bands are labelled as bands 3, 4 and 5 at low-spin. In the present work the even and odd spin sequences of band 3 have been extended by 5 and 8 transitions, respectively. A new sequence of 4 (plus 1 tentative) transitions with $\alpha = 1$ (band 3a'), has also been observed in the present work which feed into the original $\alpha = 1$ structure of band 3 at spin $11^{(-)}$. It is assumed that all the observed transitions in band 3a' have E2 multipolarity. It is also interesting to note that band 3 is connected to band 5, the relevance of which will be discussed further below. Finally, band 4 has been extended by 4 (plus 1 tentative) and 5 transitions for the $\alpha = 0, 1$ signatures, respectively.

A closer study of the band structure in Fig. 1 indicates an interesting sequence of interactions between the negative parity structures. It is evident that in the $I = 20 - 30$ spin range, the odd spin sequence of band 3 is signature degenerate with the even spin sequence of band 4 (cf. Fig. 4 below), i.e. these two sequences must be signature partners which is in contradiction to the band assignment at low spin according to Ref. [10] and as drawn in Fig. 1. Furthermore, the odd spin sequences of bands 3 and 4 interact around $I = 20$ with connecting transitions which are similar in strength to the in-band transitions. A possible idea to solve the problem would be to interchange these two sequences for spin values $I \geq 21$. However, the present way of connecting the bands leads to a much more smooth behaviour as a function of spin than would be the case if the two sequences were interchanged. We also note that there is a weak transition connecting the

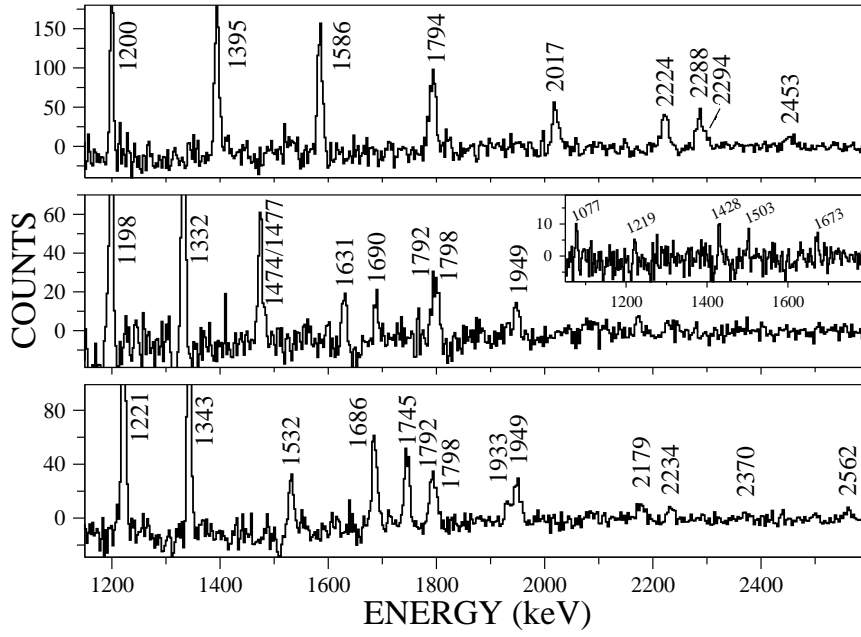


Figure 2: Coincidence spectra obtained from the E_γ - E_γ - E_γ cube discussed in the text. The top spectrum represents a sum of double gates between all transitions in the even spin sequence of band 1 from 1200 keV up to 2453 keV. The middle spectrum shows a sum of double gates between all transitions from the 246 keV γ ray up to the 1332 keV γ ray and the 1474/1477 keV transitions in the odd spin sequence of band 3. The inset to this spectrum was created from a sum of double gates between the 909 and 1077 keV transitions of the even spin sequence of band 4 and the 1503 and 1673 keV γ rays of the even spin sequence of band 3. The bottom spectrum was created from a sum of double gates between all transitions from the 242 to 1343 keV transitions in the odd spin sequence of band 4 against the 1510 keV γ ray.

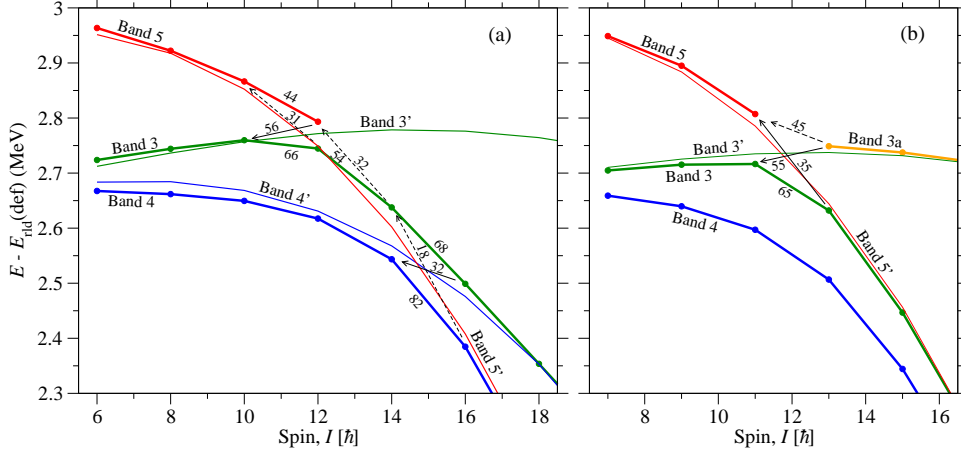


Figure 3: Illustration of the three-band crossing for the even spin (left panel) and the two-band crossing for the odd spin (right panel) negative parity states in ^{76}Rb , with the energies drawn relative to a rotating liquid drop reference. The thick lines with filled circles show the bands as they are drawn in Fig. 1. The thin lines define the smooth unperturbed bands which results in a very good description of the observed states when they interact with constant matrix elements. $B(E2)$ branching ratios calculated assuming constant $B(E2)$'s within the smooth bands and no connecting $B(E2)$'s are written out around the crossings, where observed and unobserved transitions are shown using arrows with filled and dashed lines, respectively.

even spin sequences of these two bands, i.e. a transition from the $I = 16$ state of band 3 to the $I = 14$ state of band 4 (this connection was first identified after the theoretical analysis suggested that a strong interaction should exist between the two structures). Thus, a possible (and perhaps more logical) alternative would be to interchange the even spin sequences of these two bands for spin values $I \geq 14$.

The crossings between the even spin negative parity states are illustrated in Fig. 3(a). A closer look at the observed states in that figure does not only suggest the crossing between bands 3 and 4 around $I = 14$ but also a crossing between bands 3 and 5 around $I = 11$. In order to find out if this scenario appears consistent with the observed bands, we have carried out a three-band-mixing calculation. In this calculation, three smooth unperturbed bands, labelled as 3', 4' and 5' are parameterized with a moment of inertia with a linear dependence on I . They interact with strengths which are assumed to be constant over the spin range considered, $I = 6 - 20$. With a least-square fit, all observed states in this spin range are reproduced within ± 5 keV with an interaction matrix element of 16 keV for the 3' and 5' bands that cross at $I \approx 11$ and 44 keV for the 4' and 5' bands which cross at $I \approx 15$. The interaction matrix element between the 3' and 4' bands comes out as 28 keV but it appears less well determined. Branching ratios were also calculated assuming the same transition strengths, $B(E2)$'s, occur within the smooth unperturbed bands (this assumption is roughly consistent with our interpretation below, however, at this stage it seems reasonable not to assume any specific assignment) and no transition probabilities connecting these bands. With these assumptions the calculated branching ratios do show reasonable agreement with experiment in that the observed bands follow the strongest calculated branching ratios, see Fig. 3(a). For the crossing between bands 3 and 4 (or 5' and 4') in Fig. 3a at $I \approx 15$, the strongest connecting transition with a predicted 32% branching ratio is observed whilst the one with a predicted 18% branch is not observed. At the $I \approx 11$ crossing, the $I = 12$ state of

band 5 is predicted to decay to two $I = 10$ states with about equal probability (44% and 56%) and both these transitions are observed, while for the decay of the 12^+ state of band 3, it is only the transition that is predicted to be strongest (66%) which is observed.

Band mixing calculations were also performed for the odd spin sequences. However, in this case, the two crossings between bands 3 and 5 and bands 3 and 4 are found to be too displaced in spin ($I \approx 12$ and $I \approx 20$, respectively) to make it possible to fit smooth bands with our simple formula in the spin range covering both band crossing regions. We therefore carried out simple two-band mixing calculations at each of the respective crossings. For the crossing at $I \approx 12$, band 3a is also involved, i.e. two bands can be formed if the $I = 1-11$ spin range of band 3 is combined with band 3a ($I = 13-21$) and band 5 ($I = 7-11$) is combined with the $I = 13$ and upwards spin range of band 3, see Fig. 3(b). With the non-interacting bands parameterized as discussed above and with a coupling strength of 38 keV it is again possible to fit all states in the $I = 7-17$ spin range within ± 5 keV. Furthermore, the observed bands follow the strongest predicted transitions where, for example, as indicated in Fig. 3 the $I = 13$ state of band 3 is calculated to have a 65% branching within the band but also a 35% branching to the $I = 11$ state of band 5, which appears consistent with the fact that both transitions are observed experimentally. Furthermore, the $I = 13$ state of band 3a is predicted to have its strongest branch (55%) to the $I = 11$ state of band 3, in agreement with observation, however, the band mixing calculation also indicates that there should be a strong branch (45%) to the $I = 11$ state of band 5, suggesting that it should be possible to also observe this transition. An extensive search has not been able to locate evidence for this decay, indicating that this particular decay is much weaker than predicted.

The experimental states at the crossing between the odd spin sequences in bands 3 and 4 at $I \approx 20$ (not shown in Fig. 3) are fitted reasonably well by two unperturbed bands parameterized as above. The best fit is obtained using an interaction strength of 14 keV but the fit shows little improvement compared with the assumption of no interaction between the bands. With the 14 keV interaction, the inband transitions are predicted to be about 3 times as strong as the connecting transitions. The observed transitions are so weak that it is difficult to determine their relative intensities but the prediction appears consistent with the observed decays from the 21^- state of band 4 while the two transitions from the 21^- state of band 3 have roughly the same intensities.

The new level scheme of ^{76}Rb will now be compared with the predictions of the CNS model [17, 18, 19], which does not include pairing. The CNS theoretical approach has been used very successfully to describe the high-spin rotational structures in other nuclei in this mass region, e.g. see [18, 20, 21, 22, 23, 24, 25]. Thus, one may expect that similar calculations for the high spin states in ^{76}Rb may provide a good description of the observed structures in this nucleus.

The lowest energy collective states of ^{76}Rb which are calculated in the CNS model are shown in the middle panels of Fig. 4 relative to a rotating liquid drop reference. The collectivity is essentially governed by the number of particles excited from the $N = 3$ orbitals below the $Z = N = 40$ gaps to the $g_{9/2}$ orbitals above these gaps. Thus, the bands in Fig. 4 have at least 7 particles excited. An interesting feature of the calculations is that there are several less collective configurations with fewer particles excited which are predicted to exist in the yrast region. However, no such states have been observed in the present experiment. The reason for this may lie in the fact that it is much easier to identify smooth collective structures that are close to yrast at high-spin where population occurs in fusion evaporation reactions, but another possibility is of course that the less collective structures are predicted to occur at too low an excitation energy in the calculations.

The bands in the upper panels of Fig. 4 are the unperturbed bands 3', 4' and 5', defined

at high spin in Fig. 1 and in the interaction region ($I \approx 6 - 16$) in Fig. 3. They connect smoothly to the observed bands in the low spin region, where the primed bands coincide with the unprimed bands. These bands are those which appear to correspond to the evolution of smooth structures from low to high spin and they are thus the ones that naturally correspond to the CNS configurations.

As exemplified for the [3,4] configuration in Fig. 5, most of the calculated collective configurations show coexistence between close-to-oblate and close-to-prolate shape with a well-defined barrier between the two minima. (The [p,n] notation represents the number of $g_{7/2}$ protons and neutrons in the configuration.) Consequently, we expect well defined individual bands in the two minima. In order to find interpretations for the observed bands, we have followed the lowest positive parity and three lowest negative parity bands of each signature in the middle panel of Fig. 4. Considering first the positive parity band, band 1, this is well described by the close-to-prolate [3,5] configuration which is calculated to be lowest in energy. A particularly interesting feature is the discontinuity (band crossing) that is observed for the $\alpha = 0$ signature in the experimental energy shown in the upper panel. Noting that in the cranking model, we do not try to describe the exact energies in the crossing region, it is very satisfying that the observed discontinuity ties in very well with a predicted discontinuity in the $\alpha = 0$ signature of the [3,5] configuration, see middle panel of Fig. 4. The discontinuity in the calculated band arises from the crossing between the negative signature of the third $g_{9/2}$ neutron orbital and the lowest $d_{5/2}g_{7/2}$ orbital.

For negative parity, the two lowest observed bands, 4' and 5' at high-spin, are shown in the upper right panel of Fig. 4. These bands are very well described by the two lowest calculated bands which correspond to close-to-oblate and close-to-prolate shape of the [3,4] configuration, see middle panel and compare with Fig. 5. Note especially that in both experiment and calculations, the lowest band (band 5' assigned to the prolate shape) is almost signature degenerate while the $\alpha = 1$ signature is clearly favoured in the next lowest band (band 4' assigned to the oblate shape). The third lowest band of negative parity, band 3', is shown in the left panels of Fig. 4. For this band, it is only the $\alpha = 1$ branch which is observed up to $I \approx 20$ so we cannot draw any decisive conclusions but it appears to be reasonably well described by the third lowest calculated band of negative parity, which is the near-prolate band with a [4,5] configuration.

With the assignments specified above, the differences between calculated and experimental energies of the states are shown in the lower panels of Fig. 4. For spin values $I \gtrsim 15$, these differences are considerably smaller than the expected [19] accuracy of ± 1 MeV. Furthermore, the differences are similar for all the bands, i.e. they come close to 0.5 MeV for $I \approx 15$ and lie roughly in the range 0-0.5 MeV for $I = 25 - 30$. This latter fact indicates that the relative properties of the bands are well reproduced in the calculations.

The differences in the lower panels of Fig. 4 become more positive for low spin values indicating the importance of the pairing energy, which is not included in the CNS calculations. These pairing energies are however small for the odd-odd ^{76}Rb nucleus, a feature which can be concluded independent of our interpretation from the fact that the moments of inertia for the different bands come close to the rigid body value at low spin values. However, in order to evaluate this further we have also carried out calculations including pairing in the formalism presented in Ref. [26], with particle number projection and with energy minimization not only in the shape degrees of freedom, ε_2 , γ and ε_4 but also in the pairing degrees of freedom, Δ and λ . In agreement with the discussion above, the contributions from pairing are found to be small at low spin values and they decrease with increasing spin. These pairing energies will not change the general structure which means that, for example, the potential energy surfaces with pairing included are found to be very similar to those shown in Fig. 5 with two well separated

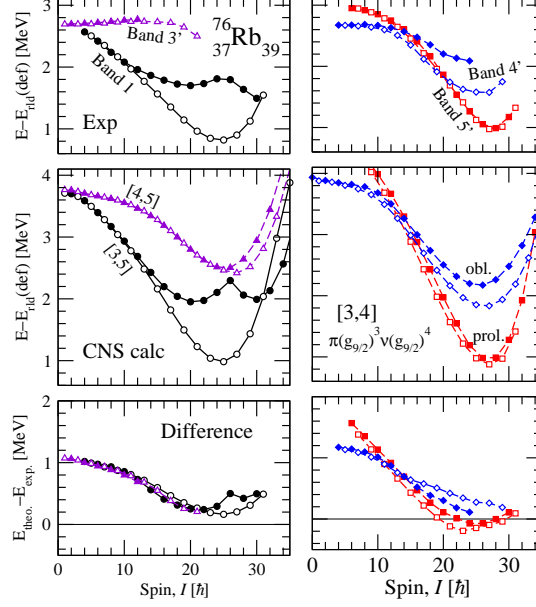


Figure 4: Observed (upper panels) and calculated (middle panels) rotational bands in ^{76}Rb and their difference (lower panels), with the two lowest negative parity bands which show shape coexistence in the panel to the right and the lowest positive parity band and third lowest negative parity band to the left. The observed bands are drawn as the smooth bands 3', 4' and 5' in the interaction region, see Fig. 3 and connect smoothly to the observed states at low and high spin, see text for details. Filled (open) symbols are used for even (odd) spin states and full (dashed) lines for positive (negative) parity.

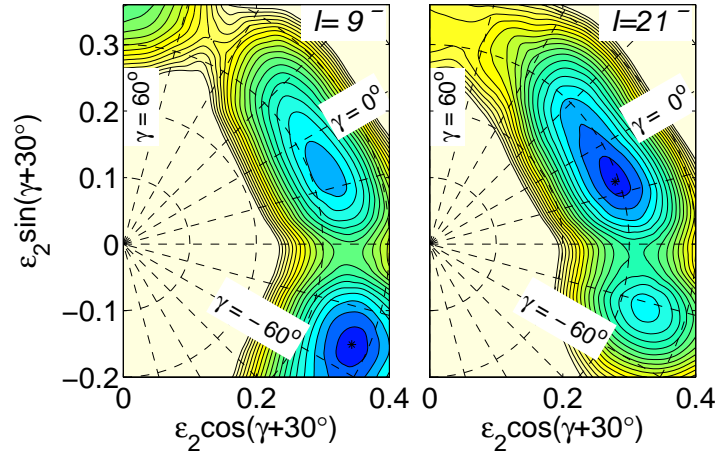


Figure 5: Calculated potential energy surfaces for the $I = 9$ and $I = 21$ states of the $[3,4]$ configuration. The contour line separation is 0.2 MeV.

minima. This supports our analysis which we have preferred to carry out mainly in the unpaired formalism, making our conclusions more transparent, mainly due to the unique possibilities to fix configurations in an extended spin range.

The most interesting result in our analysis is the coexistence of close-to-prolate and close-to-oblate bands of both signatures for the [3,4] configuration. This coexistence is illustrated in the potential energy surfaces of Fig. 5 and is seen to give an excellent description of the observed bands. Furthermore, it is only when two coexistent shapes are considered for the [3,4] configuration that it appears possible to find a reasonable explanation of the band referred to as 4' in Fig. 1 with its large signature splitting. In view of the excellent description within the CNS approach of the level schemes in neighbouring nuclei [21, 22, 24, 25] and also in other regions of the (Z, N) chart, we consider that this conclusion about coexistent shapes in the $I = 15 - 30$ spin range is very reliable. Considering neighboring nuclei, we have also carried out CNS calculations for ^{77}Rb which results in a description of all high-spin bands with a similar accuracy to that achieved in ^{76}Rb , but where only one band is observed for each configuration. It is also interesting to note that the 'new type of band crossing' discussed for ^{77}Rb in Ref [27], is straightforward to understand in the CNS formalism as a crossing between bands with a different number of high- j particles, see e.g. Ref [28] where such crossings in the $h_{11/2}$ shell are discussed.

For ^{76}Rb , it is gratifying that the observed and calculated bands in the $I = 10 - 15$ spin range cross in very much the same way in experiment and calculations. This is especially true for bands 4' and 5' which cross around $I = 15$ in a very similar way to the oblate and prolate bands of the [3,4] configuration that has been assigned to them, see Fig. 4. This makes it tempting to also speculate about the presence of shape coexistence around the band heads, but a more thorough investigation of such a scenario is outside the scope of the present letter. The band mixing calculations show that the even spin states of the oblate and prolate structures interact with a matrix element close to 50 keV at $I \approx 15$ while the odd spin states interact with a smaller matrix element which is less well determined around $I = 20$. This can be compared with the much larger interactions for the coexistent shapes at low spin for $^{72-78}\text{Kr}$ [7], suggesting a decreasing matrix element with increasing spin. This is also consistent with theoretical calculations [29] including large amplitude vibrations, which indicate that the spread of the wave-function over different shapes reduces with increasing angular momentum.

It is also interesting to consider how the bands evolve for spins higher than presently observed. At high spin, all configurations have a tendency to approach termination, i.e. the shape trajectories will slowly approach the non-collective limit at $\gamma = (-120, 60^\circ)$ corresponding to the left border of the energy surfaces in Fig. 5. As seen in Fig. 4, the close-to-oblate branch of the [3,4] configuration is predicted to cross the close-to-prolate branch for spin values just beyond $I = 30$. The reason appears to be larger components of (holes in) the $f_{7/2}$ shell which thus have an important contribution when building spin for $I \gtrsim 30$. Indeed, with no contribution from the $f_{7/2}$ shell, the maximum spin in the [3,4] configuration is $I_{\max} = 35$ but no real termination is predicted at this spin value, e.g. see [23, 25].

In summary, high-spin states have been populated in ^{76}Rb using the $^{40}\text{Ca}(^{40}\text{Ca}, 3\text{pn})$ reaction. This has led to extensions of all the previously known rotational bands. From the way the three negative parity bands (of both signatures) interact, they are redefined into structures which evolve smoothly with spin where approximate interaction strengths between these structures have been extracted. They are compared with Cranked Nilsson-Strutinsky (CNS) calculations which provide an excellent description of all bands. In particular, two of the bands can be understood as

being built from the same configuration (in terms of the number of $g_{9/2}$ particles), but arising from different - near coexistent - close-to-prolate and close-to-oblate nuclear shapes. This appears to constitute the best example of such coexistent structures of similar configurations at medium spin. The comparison between the observed and calculated bands suggests that the coexistence can be followed down to the band heads where, contrary to the $I = 20 - 30$ spin range, the close-to-oblate structure is calculated to be lowest in energy. Finally, considering the special features of band crossings and coexistence observed in ^{76}Rb it would be very interesting to carry out a new experiment to get a more complete understanding of these features; hopefully also making it possible to extend the bands to higher spins where their termination or non-termination [23, 25] is another important fingerprint of their configurations.

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